LOW-POWER GAS DETECTION BEACON FOR HAZARDOUS AREA APPLICATIONS

by

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A thesis submitted to the School of Graduate Studies in partial fulfillment of the requirements for the degree of Master of Engineering.

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May 2024

St. John's, Newfoundland and Labrador, Canada

Abstract

Sensors are critical in industrial applications as information of any given process must be relayed from the environment back to a human or computer for interpretation and action. Particularly in the Oil and Gas industry, certain environmental hazards exist that must be respected, and such areas are classified with a “Hazardous Area” designation as specified by the International Electrotechnical Commission, a globally recognized standard. These areas have restrictions for personnel and equipment to operate as safely as possible. Hardwired field devices are designed and certified for specific areas and most wireless sensors, if they’re acceptable at all, are developed with an integrated explosion-proof enclosure such that the circuit design requirements are not as restrictive as otherwise would be without this level of protection.

Gas detection methods are available in both fixed and portable designs. Fixed designs provide general operational coverage and portable are often utilized when more specific coverage is required (during non-routine maintenance, for example). When designing hardwired field devices for coverage in hazardous areas, special considerations are required such as the use of intrinsically safe barriers between the field and a designated “safe’ or potentially less-dangerous category of Hazardous Area. The use of batteries can be advantageous due to electrical isolations and protection techniques. Most portable gas detection methods are secured to a person in the general area of their mouth and nose and alarm in the presence of gas. This inherently means when gas is detected it is already near the face of personnel.

This work explores the potential to leverage Bluetooth Low Energy to develop a beacon for gas detection that can alert personnel in the area with a sufficiently low transmission power such that the International Electrotechnical Commission safety guidelines are respected. It can also be integrated into existing portable gas detectors such that the warning is available from a meaningful distance.

Acknowledgements

The success of this thesis could not have been possible without the endless support of friends, family, and colleagues. I would like to take advantage of this space to acknowledge some of the amazing people in my life who generously gave their time, knowledge, and consistent belief in me especially at those critical times when faith in myself was waning.

- Dr. Vlastimil Masek – Truly a role model for me: morally and professionally. Thank you for your open-door with a smile, insightful advice, and endless encouragement.
- Setpoint AE – Thank you for supporting this journey: personally, professionally, and financially.
- My parents: Carl and Helen Staubitzer – Thank you for believing in me and teaching me that investing in yourself is the most valuable thing one can do.
- Thomas House – Thank you for the countless nights spent discussing science, engineering, politics, philosophy, music, art, and everything in between.
- Tim and Renee Smith – Thank you for your guidance through this thesis from both technical and practical perspectives.

Thank you to everyone I've had the pleasure of working with and learning from along this journey.

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List of Abbreviations

ADC	Analog/Digital Converter
AM	Amplitude Modulation
AoA	Angle of Arrival
AoD	Angle of Departure
ATT	Attribute Protocol
BLE	Bluetooth Low Energy
FM	Frequency Modulation
FSK	Frequency Shift Keying
GAP	Generic Access Profile
GATT	Generic Attribute Profile
GFSK	Gaussian Frequency Shift Keying
I/O	Input/Output
IDE	Integrated Development Environment
IEC	International Electrotechnical Commission
IoT	Internet of Things
ISM	Industrial, Scientific, Medical
LEL	Lower Explosive Limit
MESG	Maximum Experimental Safe Gap
MIC	Minimum Ignition Current
NARL	North Atlantic Refining Ltd.
PLC	Programmable Logic Controller
PWM	Pulse Width Modulation
RF	Radio Frequency
RIO	Remote Input/Output
SIG	Special Interest Group
SoC	Software on a Chip
UEL	Upper Explosive Limit
UUID	Universally Unique Identifier

List of Symbols

E	Electric Field
M	Magnetic Field
P	Power
R	Resistance
V	Voltage
Z_{th}	Threshold Energy
λ	Wavelength

Chapter 1

Introduction

Civilization as we know it would not be possible without the foundation laid by the incredible technological advancements of the industrial revolution which had immeasurable benefits to every major industry. The modern world rests upon a support-structure of technology that is constantly improving to do as much as possible and as efficiently as possible. One such area, critical to industrial operation, is the interface between technology and the environment for the collection of data. This interfacing uses devices known as "sensors". Simple examples can be observed in nature through the development of better-suited eyes for nocturnal hunters (light-sensors) or improved hearing as prey (sound-sensors). Complex organisms possess and rely upon sensors that can accurately measure data for a given biological system to use. Technology mimics this process of evolution with advancements often made possible by better data collecting sensors, either novel or improved, resulting in higher quality information.

A thermometer or “thermo-meter” is simply a meter that measures thermal energy. Current thermometer technology can be found in every aspect of modern life and there are countless industrial applications that would otherwise be impossible if thermo-metering technology was not available. Sensors in industrial settings include but are not limited to flow, pressure, temperature, and level and while accuracy and precision are often critical, they’re not the only important factors. These sensors are generally designed to provide a 4-20 mA signal that is then interpreted by software (often a programmable logic controller (PLC)) and then calibrated to scale as required. If the communication link between the sensor and PLC which interprets and acts upon this data is faulty, then the data received can be considered unreliable. Detection and metering of environmental information is only part of the bigger picture as the information must be reliably delivered to a system for it to have practical value. There are many methods of evaluating input signal quality such as a “heartbeat”, which is a periodic and expected communication which would indicate a problem if not received.

One such industry is the fuel of the industrial revolution itself, the energy sector and in particular, oil and gas. Complex engineering is required to achieve impressive feats such as energy generation. Great care must be taken in certain locations due to hazardous conditions inherent in the process. Gases may explode and particles may combust at certain temperatures or due to a spark/static energy build-up on circuitry. The concept of intrinsically safe electronics was envisioned and a standard for industrial applications and safety was created and is now a required certification by law in many countries. Equipment is designed to meet these standards to mitigate hazards to personnel, equipment, and the environment.

Industrial hazards are often controlled using a technique known as “Hierarchy of Controls” which begins with eliminating the hazard entirely as the most effective option and personal protective equipment as the least effective option. Substitution follows as maybe a less dangerous option may be suitable. If other options are unavailable, engineering controls are developed to isolate people from the hazards where possible. When exhausted and personnel must still interact with a hazardous area, administrative controls are developed to help with training and work-place consciousness. With personal protective equipment as the last and least effective control between a safely mitigated hazard and potential injury, improvements to this type of sensing and detection are paramount.

1.1 Problem Statement

Radio technology is generally not used in hazardous environments due to the inherent explosion risk and the design costs associated with meeting certification standards. Radios and portable devices such as cameras, tablets and laptops may achieve appropriate ratings for certain areas depending on the area-of-use requirements. Even with certification, the use of these devices is managed with strict oversight and personnel must follow the offshore installation’s procedures. These include requirements to obtain permission and signatures to authorize use and certify responsible parties have confirmed the equipment is in proper condition and all certifications are still valid. This type of device is portable (non-fixed) and therefore follows slightly different regulations than those of fixed objects.

Fixed wireless devices are currently utilized in hazardous industrial settings and are designed with an integrated explosion-proof containment. This is a perfectly acceptable means to achieve hazardous area certification. There are many factors that an enclosure design must follow but are different from those without such an enclosure (generally less restrictive for the electronics). For example, output/transmission power from the antenna isn’t as restricted due to the protection provided by the enclosure.

This work explores the potential to leverage Bluetooth Low Energy (BLE) to develop a beacon for gas detection that can alert personnel in the area with a sufficiently low transmission power such that the International Electrotechnical Commission safety guidelines are respected, which can potentially be integrated into existing portable gas detectors and that the warning is available from a meaningful distance.

1.2 Motivation

This research was heavily motivated by the tragic explosion at the Come By Chance Refinery. Officially known as North Atlantic Refining Limited (NARL), is an oil refinery located in the community of Come By Chance in Newfoundland and Labrador, Canada on the eastern shore of Placentia Bay. The explosion not only caused significant property damage and financial losses but seriously injured eight workers: one of which ultimately succumbed to injury six weeks later. The reality of safety protocol is that its often written after a tragedy has occurred and that, for those involved, its too late. The motivation of this research is that the results contribute to the prevention of similar incidents in the future.

1.3 Contributions

This thesis documents the design, testing, and refinement of a beacon capable of detecting the presence of gas and transmitting a beacon signal using Bluetooth Low Energy. This design incorporates a novel construction of software on a chip (SoC) in which the network core and application core are separate, allowing for significantly lower power consumption during deep sleep as well as transmission (to achieve hazardous area certification without the use of an explosion-proof enclosure).

The experimental results provide insight into the possibilities of this Bluetooth technology specifically regarding design configurations that push the limits of "low energy" to achieve hazardous area compliance while maintaining a degree of data transmission signal quality and practical range that could be considered useful.

The subsequent analysis of these results provides both a qualitative and quantitative assessment of the device. Using the design criteria as a metric for success, areas of improvement are identified, and further development is suggested. It is the hope that the results achieved will support further development of wireless beacons for use in hazardous areas.

1.4 Thesis Outline

This thesis is divided into the following seven chapters:

Chapter 2 reviews background information relevant to this work. Section 2.1 gives a brief history and foundations of wireless communication principles followed by an introduction to Bluetooth technology in Section 2.2. Section 2.3 describes typical sensors in the offshore oil and gas industry. Section 2.4 covers the concept of hazardous areas and the safety requirements outlined by the International Electrotechnical Commission (IEC) which will be the guiding criteria for combining all background content into this thesis' design which is detailed in Chapter 4.

Chapter 3 introduces modern methods of powering field devices and options for small/portable electronics to provide insight into the possibilities and considerations to deliver power in volatile and sensitive environments.

Chapter 4 guides through the beacon design process beginning with the state flow diagram and concept. Programming the SoC and modifying system parameters to achieve the desired functional and technical specifications. Then optimize the radio operation with a sufficiently low power to meet the restrictions detailed in Section 2.4. Once optimized, integrating a gas sensing circuit for monitoring.

Chapter 5 details the construction and experimentation with the device. Although testing that the design is, in fact, explosion-proof will be left to the appropriate authorities, practical operation given the certification-based design criteria will be considered as a successful endeavor.

Chapter 6 compares the experimentation results with the expectations and then examines any discrepancies to suggest potential sources and future improvements to address them.

Chapter 7 is the final chapter that will summarize and conclude the research, express lessons learned and suggestions for expansions into future work.

Chapter 2

Background

This chapter provides high-level insight into three aspects relevant to this thesis: wireless communication, industrial sensors, and hazardous area classifications. Wireless communication has revolutionized data transmission by eliminating the need for physical connections, providing flexibility and scalability in industrial environments. Industrial sensors are instrumental in gathering real-time data to monitor and control various processes, enhancing efficiency and productivity. However, industrial operations often encounter hazardous environments, which necessitate careful classification and mitigation strategies to ensure safety and regulatory compliance. Understanding of these interconnected topics and their significance in modern industrial settings is recommended.

2.1 Wireless Communication

The history of wireless communication begins with understanding electromagnetic waves. James Clerk Maxwell (1831 – 1879), a Scottish physicist, laid the foundation for the study of these waves in the 19th century with the formalization of his now fundamental set of four equations that describe their behavior [1]. Heinrich Hertz (1857 – 1894), a German physicist, then expanded on that work and conducted experiments in the late 19th century that proved the existence of electromagnetic waves, which he named Hertzian waves [2]. Guglielmo Marconi (1874 – 1937), an Italian inventor and electrical engineer, built upon that work to develop the first practical system of wireless communication, "wireless telegraphy" now commonly known as radio having won a Nobel Prize in 1905 together with Karl Ferdinand Braun for their contributions to the field. Marconi transmitted the first radio signal across open water in the summer of 1895, and later developed this technology for ship-to-shore communication. This laid the foundation for the widespread use of radio communication in the 20th century upon which modern civilization is supported [3].

2.1.1 Radio Communication

Radio communication can be loosely defined as the transmission of meaningful signals by the modulation of electromagnetic waves with frequencies below those of visible light. Electromagnetic radiation propagates by means of oscillating electromagnetic fields. Information is carried by systematically changing (modulating) some property of the radiated waves such as amplitude, frequency, or phase. The waves may then be received and with appropriate knowledge of the modulation process they can be meaningfully interpreted.

2.1.2 Wavelength

Wavelength is defined as the distance between successive peaks measured in units of length and represented by the Greek letter lambda (λ) [4].

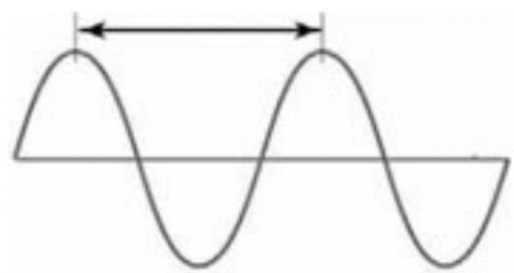


Figure 1 - Definition of Wavelength (λ)

2.1.3 Amplitude

Amplitude is the maximum strength/intensity of the electric (E) and magnetic (M) fields which propagate perpendicularly to each other as illustrated in Figure 2. The energy in any part of the electro-magnetic wave is the sum of the energies of the electric and magnetic fields which is at a maximum at the origin and reduces proportionally with distance from the source and time [4].

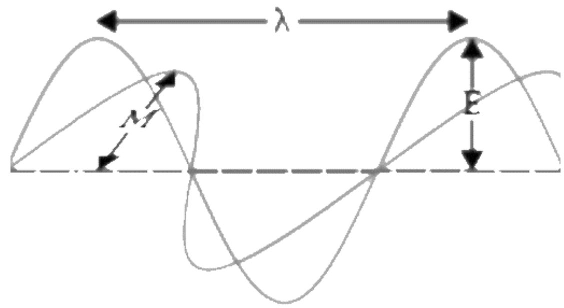


Figure 2 - An Electro-Magnetic Wave

2.1.4 Frequency

Frequency is a measure of how often a wave oscillates and is usually measured in hertz (Hz). A wave with a high frequency oscillates more times per second than a wave with a low frequency [5].

2.1.5 Phase

Phase refers to the position of the wave at a specific point in time. Two waves that are considered "in phase" will have the same phase angle with respect to a known reference, while two waves that are "out of phase" will have different phase angles [5].

2.1.6 Modulation Overview

A carrier wave is chosen for specific operating frequency bands to comply with regional law for radio communications. The carrier wave is modulated by the desired message signal, which changes the characteristics of the wave thereby encoding a message. When the modulated carrier wave is received, the receiver demodulates/decodes the signal and can recover the message [6]. The carrier wave itself carries no information; it is just a host. There are trade-offs between various modulation techniques which must be understood when designing wireless communication systems. A commonly known example of everyday modulation with an easy comparison are amplitude modulation (AM) and frequency modulation (FM) for radio broadcasting.

AM is a method of encoding a message onto a carrier wave by varying the amplitude of the wave with a fixed frequency. FM is a method of encoding a message onto a carrier wave by superimposing a lower frequency wave onto the higher frequency carrier yet fixed amplitude [6].

The tradeoffs between these two modulation methods are verifiable with a car radio driving too far from a radio tower. AM will travel much farther than FM due to the lower frequency wavelengths and isn't as poorly affected by solid objects/line of sight issues. However, FM can transmit much more data than AM and as such can have higher sound quality and meta information such as song title, artist, lyrics etc.

Frequency Shift Keying (FSK) shown in Figure 3 is another method of modulation and is achieved by shifting the frequency of a carrier signal to represent the binary states of 0 and 1.

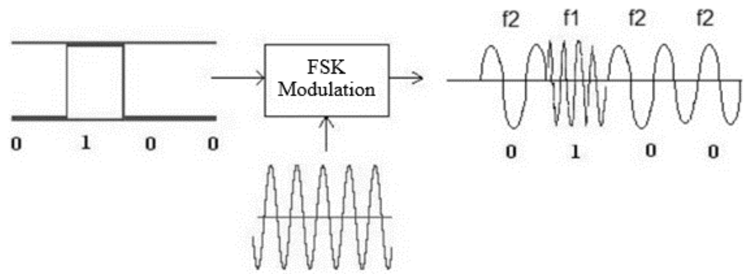


Figure 3 - Frequency Shift Keying

A modification to FSK in which states between -1 and 1 is first passed through a Gaussian filter to shape the pulses before they are modulated is known as Gaussian Frequency Shift Keying (GFSK). The frequency response of this filter is very narrow, and this filtered input results in a spectral width which is reduced compared to FSK. Abrupt changes in frequency in FSK are filtered in GFSK, making the transitions at the start of symbol periods smoother [7]. GFSK is used by modern Bluetooth technology.

2.2 Bluetooth

Bluetooth is a standardized wireless technology for short-range communication. The history of Bluetooth dates to the late 1990s, when Ericsson, a Swedish telecommunications company, began developing a technology to replace the cables connecting various devices, such as mobile phones, computers, and headphones. In 1998, Ericsson formed the Bluetooth Special Interest Group (SIG), a group of companies that included IBM, Intel, Nokia, and Toshiba, to develop and promote the technology. The group was named after Harald Bluetooth, a 10th century Danish king who united warring tribes into a single kingdom, like how the technology was designed to unite different devices [8].

The first version of the Bluetooth specification, version 1.0, was released in 1999, and it provided a way for devices to connect wirelessly using a low-power radio frequency. It had a range of about 10 meters and a data transfer rate of 1 Mbps. Since then, Bluetooth technology has evolved and improved significantly. Newer versions of the specification, from Bluetooth 1.0 through to the most recent 5.3 have been released, providing faster data transfer rates, lower power consumption, and increased security features. Bluetooth has become a widely adopted technology which can now be found in a wide range of devices, such as smartphones, laptops, headphones, speakers, and fitness trackers. It is also used in various applications, such as wireless audio streaming, and wireless device control [9].

2.2.1 Bluetooth Classic

Bluetooth Classic refers to the original version of Bluetooth technology, which is also known as "Basic Rate" or "BR" Bluetooth. This version of Bluetooth is based on the original Bluetooth specification, version 1.0 and 1.1. In this original version, GFSK, as introduced in Section 2.1.6, was used because it provides a balance between power efficiency and data rate (1, 2 or 3 Mbit/s) [10].

The modulation method allows for low-power and low-cost devices to communicate over short distances. GFSK is also relatively immune to interference from other electronic devices, which makes it well-suited for use in environments where there may be other electronic devices present. Bluetooth GFSK uses a modulation index of 0.5, this means that the frequency of the carrier wave is shifted by 50% of the bit rate. The specific frequency that is used in Bluetooth GFSK is 2.4GHz, which is within the ISM (Industrial, Scientific, and Medical) band and is unlicensed for use in most countries [10].

2.2.2 Bluetooth Low Energy

Bluetooth Low Energy (BLE), also known as “Bluetooth Smart” or Bluetooth 4.0, is a version of Bluetooth originally developed by Nokia called “Wibree” before acquisition by the Bluetooth SIG. BLE is designed for low-power, low-bandwidth applications and is intended for use in devices that require long battery life and low power consumption. BLE is optimized for applications such as Internet of Things (IoT) devices, wearables, and other low-power devices.

Two primary differences between BLE and Bluetooth Classic are the power consumption and data transfer rate. BLE also has a lower data transfer rate than Bluetooth Classic, typically around 1 Mbps, which is sufficient for most low-power applications. The data protocol was changed to create low-duty-cycle transmissions, or a very short transmission burst between long periods. In addition to extremely low-power sleep modes, the low duty cycle allows a Bluetooth Smart product to operate for many years on a coin cell or, as will be explored in this thesis, an energy harvesting device [10].

BLE uses a different communication protocol than Bluetooth Classic, known as the Generic Attribute Profile (GATT) and it defines the way that two Bluetooth Low Energy devices communicate using techniques known as Services and Characteristics. It makes use of a generic data protocol called the Attribute Protocol (ATT), which stores Service, Characteristic, and other related data in a simple lookup table using 16-bit IDs for each entry [10].

BLE devices can communicate in two ways: broadcasting and direct connection. In broadcasting mode, BLE devices send out small packets of data periodically, and any other device within range can receive and interpret the data. In direct connection mode, BLE devices establish a direct connection with each other and can exchange data in a more efficient manner using GATT. This broadcast feature will be leveraged in the design phase and is further explained in Section 2.2.5.

2.2.3 Bluetooth 5.0 to 5.3

Bluetooth 5.0 was a significant upgrade capable of data transfer at double the possible speeds of version 4.2 and greatly expanded the connection/transmission range. One of the biggest changes that resulted from the upgrade to 5.1 is the use of different direction-finding methods. These different methods are Angle of Arrival (AoA) and Angle of Departure (AoD), which allows receiver and transmitter pairs to know exactly where they are in relation to each other. Previous technologies would have to loosely estimate the distance between devices [10].

Slight improvements in the caching and pairing processes made advertising and discovery much more efficient. Advertising is the term used for the process that devices use to announce they are ready to pair. The improvement in this area is mostly due to a technique called randomized channel indexing. Devices using previous versions of Bluetooth would have to go through a specific set of channels to discover and connect to the partner device. Now the channels can be accessed at random without having to run through each of them in sequence. This makes the process faster and less likely to experience interference in areas when many Bluetooth devices are connected simultaneously [11].

Bluetooth 5.2 introduced Low Energy power control. Low energy as mentioned, was introduced with Bluetooth 4, but it was not sophisticated enough to be used with most practical applications, like audio streaming and was limited to small-scale operations, such as with fitness watches or computer peripheral devices [11]. Bluetooth 5.2 allowed more information to be transmitted over lower bandwidth and at lower power.

The most innovative feature of 5.2 is the use of Isochronous Channels. This takes the Dual Audio feature farther, allowing for multiple connections of Bluetooth devices to single source which allows for automatic and seamless switching between devices such as cars, cellphones, and laptops. The main relevant improvements with 5.3 are better efficiency, less signal interference, and increased security.

2.2.4 Advertising and Broadcasting

The Generic Access Profile (GAP) is responsible for controlling the connections and advertising for Bluetooth communication. Of the 40 available channels that span the bandwidth range, channels 37, 38 and 39 are used only for sending advertising packets, the rest are data channels as illustrated in Figure 4 (channel ranges zero to ten and eleven to thirty six have been omitted for space) [12].

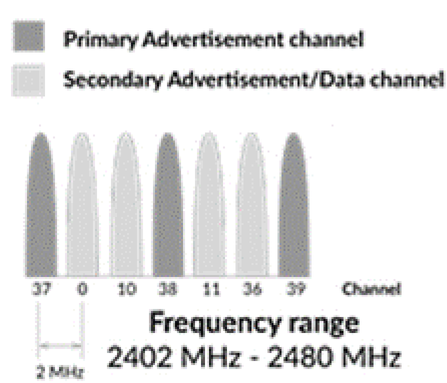


Figure 4 - Bluetooth Advertising Channels

GAP governs device discoverability and in which ways it may be interacted with by other devices once connected. While this generic access profile can define various roles to classify devices, two main categories are easily identifiable: peripheral and central.

Peripheral devices are often smaller in physical size and are low power with resource restrictions that connect to a more capable central device. Some examples of this are heart rate monitors or wireless earbuds. Central devices are the main “more capable” device to which peripheral devices connect to offload heavier processing duties or for things like storage/memory.

2.2.5 Advertising Process

Advertising with GAP has two options “Advertising Data” and “Scan Response”. Both are identical and may contain up to 31 bytes of data, however the advertising data is the only mandatory option as this will be constantly transmitted by the peripheral to communicate with a central device to indicate it exists [13].

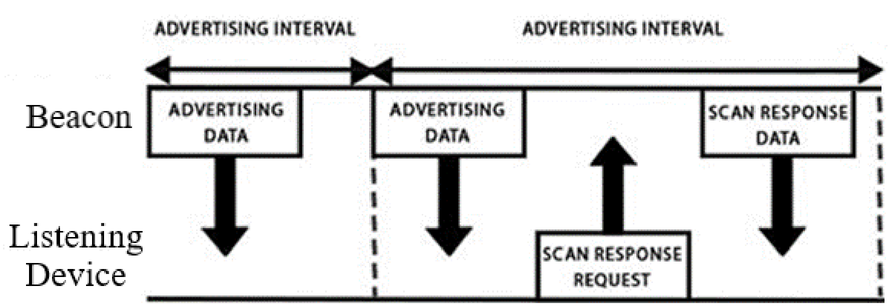


Figure 5 - Bluetooth Advertising Exchange

The advertising interval is customizable and is retransmitted periodically. This is an advertisement to allow pairing and any device in range can receive the broadcast and request a subsequent scan response [13]. With the inclusion of a small amount of custom data inside the advertising or scan response, a peripheral can send one-way data to any listening device which is known as "broadcasting" and is used in industry by devices such as Apple's iBeacon in which the main advertising data contains a "Manufacturer Specific Data" field or the Eddystone standard developed by Google.

2.2.6 Conclusion

This introduction of the history and foundation of wireless communication with the basic concepts of electromagnetics and relatable real-world examples introduces the reader to the framework within which this research will explore. Expanding more specifically into signal modulation and the development and utilization of the Bluetooth protocol provides insight into the relevant specifics for this application.

2.3 Industrial Sensors

An industrial sensor is a device that is used to measure a specific physical or chemical property of a system or environment. Industrial sensors are widely used in various industries, such as manufacturing, mining, oil and gas, and transportation. Some examples of industrial sensors include:

Temperature: They can be critical in applications such as industrial machinery, chemical processes, and temperature of food or medicine [14].

Pressure: They can be used in applications such as measuring the pressure of fluids in pipes or gases in tanks [15].

Flow: Like pressure sensors, they can be used in applications such as the flow of fluids or gases in pipes, air in ventilation systems [16].

Level: Can be used to monitor the level of liquids in tanks, powders in silos, and granular materials in hoppers [17].

2.3.1 Signal Interface

Industrial sensors are typically designed to be robust and durable, able to withstand harsh environments and can be used in remote locations missing infrastructure with wireless as a requirement. Although there are many types of sensors with various designs, ultimately there are only a few ways in which they relay information.

Analog: Some sensors produce an analog signal, which is a continuous electrical signal that varies in amplitude and frequency. The analog signal can be processed by electronic devices, such as data acquisition systems, which convert the analog signal into digital data that can be processed by computers and other digital devices. The industry standard for an analog signal is 4-20 mA [18].

Digital: Many sensors produce a digital output, which is a discrete electrical signal that can take on only a limited number of values. Digital sensors typically output a digital signal, such as a pulse width modulation (PWM) signal, which can be read by a digital input on a microcontroller D/O as a binary or PWM [19].

Wireless Communication: Some sensors use wireless communication, such as Bluetooth, Zigbee, or Wi-Fi, to transmit data to a host device. Wireless communication allows for easy integration with other devices and can be used in applications where a wired connection is not possible or practical. Signals are processed and transmitted wirelessly using desired protocol and technology.

2.3.2 Combustible Gas Sensor

Gas sensors can generally be divided into "passive" and "active" categories. A variety of "passive" technologies are employed and the most common is the electrocatalytic. The "active" types use technology leveraging infrared absorption for detection [20]. An infrared source emits a signal many times a second and the amount of energy observed by the detector correlates to a measure of gas concentrations.

2.3.3 Passive Sensing

Electrocatalytic sensors are widely used in a variety of industries as single-point detectors for combustible gases. They function on the principle that combustible gas oxidizes to produce heat and this temperature change can be converted with the use of a Wheatstone Bridge to an electrical signal which can then be processed and alert the presence of gas [20].

2.3.4 Active Sensing

Using infrared radiation to measure gas concentrations relies on the principle that certain wavelengths are absorbed as it passes through gas in an area. They require a light source and receiver and compare the light intensity at two specific wavelengths: one at the absorption wavelength and one unaffected wavelength used for reference [20].

2.3.5 Conclusion

Even with the same purpose, industrial sensors come in various designs each with positives and negatives. The trade-offs must always be accounted for as they aren't just cost but also accuracy, precision, durability, and ruggedness to name a few. The application must be carefully considered along with environment and the criticality of the data required.

2.4 Hazardous Area Classification

Hazardous Area Classification is the process of identifying and evaluating the potential hazards present in each area. Designing and implementing appropriate safety measures and equipment for use in that area rely on this information. This process is critical in industries where hazardous materials, such as flammable gases, liquids, or dusts, are present, due to the risk of explosion or fire. The International Electrotechnical Commission has well-defined safety requirements and is an industry standard as a governing authority.

Zones are divided by the IEC into the following three categories:

> **Zone 0**: An area where an explosive atmosphere is present continuously or for long periods.
>
> **Zone 1**: An area where an explosive atmosphere is likely to occur in normal operation.

Zone 2: An area where an explosive atmosphere is not likely to occur in normal operation, and if it does occur, it will exist only for a short period.

2.4.1 Explosive Gas Atmosphere

The IEC 60079-0 [21] standard defines Group II under its section 4.2 as follows:

"4.2 Group II

Electrical equipment of Group II is intended for use in places with an explosive gas atmosphere other than mines susceptible to firedamp. Electrical equipment of Group II is subdivided according to the nature of the explosive gas atmosphere for which it is intended.

Group II subdivisions:

- IIA, a typical gas is propane
- IIB, a typical gas is ethylene
- IIC, a typical gas is hydrogen

NOTE 1 This subdivision is based on the maximum experimental safe gap (MESG) or the minimum ignition current ratio (MIC ratio) of the explosive gas atmosphere in which the equipment may be installed. (See IEC 60079-12 and IEC 60079-20)."

Table 1 combines this information with each gas' respective ignition energy in micro-Joules.

Table 1 - Gas Groups and Associated Ignition Energy

Group Classification	Typical Gas Present	Ignition Energy (μJ)
Group IIA	Propane	160
Group IIB	Ethylene	80
Group IIC	Hydrogen	20

2.4.2 Radio Frequency in Group II Areas

In hazardous areas the use of radio frequency (RF) energy can pose a potential ignition risk. To minimize this risk, the IEC has established guidelines specifically for RF energy thresholds through a combination of 60079-0 [21] and 60079-14 [22], for the safe use of RF in the respective areas. It establishes limits for the maximum permissible RF energy levels that can be present based on the type of explosive atmosphere and the frequency/behaviour of the RF energy. IEC 60079-0 [21] defines the following:

3.32.2 Continuous Transmission: Transmission where the duration of the pulse is greater than half of the thermal initiation time.

3.32.3 Pulsed Transmission: Transmission where the duration of the pulse is shorter than the half of the thermal initiation time, but the time between two consecutive pulses, however, is longer than three times the thermal initiation time.

3.32.4 Thermal Initiation Time: Time (over which threshold power is averaged) during which energy deposited by the spark accumulates in a small volume of gas around it without significant thermal dissipation.

3.32.5 Threshold Energy (Z_{th}): for a pulsed radio-frequency discharge, the maximum energy of the single pulse which can be extracted from the receiving body.

The regulations in IEC 60079-14 [22] state:

"Structures and antennas located in hazardous areas can act as receivers for transmissions from outside of the hazardous area. The threshold power of radio frequency (9 kHz to 60 GHz) received in the hazardous area for continuous transmissions and for pulsed transmissions whose pulse durations exceed the thermal initiation time shall not exceed the values shown in Table [1] - Radio Frequency Power Thresholds. Programmable or software control intended for setting by the user shall not be permitted." Table 2 presented is the aforementioned "Table [1] - Radio Frequency Power Thresholds".

Table 2 - Radio Frequency Power Thresholds

Equipment For	Threshold Power (W)	Thermal Initiation Time (µs)
Group IIA	6	100
Group IIB	3.5	80
Group IIC	2	20

"For pulsed radar and other transmissions where the pulses are short compared with the thermal initiation time, the Threshold Energy values Z_{th} shall not exceed those given in Table [2]." Table 3 presented is the aforementioned "Table [2] - Radio Frequency Energy Thresholds".

Table 3 - Radio Frequency Energy Thresholds

Equipment For	Threshold Energy Z_{th} (μJ)
Group IIA	950
Group IIB	250
Group IIC	50

2.4.3 Flammable Gases

The preceding guidelines are determined in the pursuit of removing one of the three required conditions for an explosion to occur. A combustible gas must be present in the presence of oxygen and ignition source such as a spark or flame. Successfully removing one of the three will prevent an explosion. Gasses have a particular concentration which they are combustible. There are two limits of interest: a Lower Explosive Limit (LEL) and Upper Explosive Limit (UEL) in which the gas mixture is too lean or too rich to burn illustrated in Figure 6 [23].

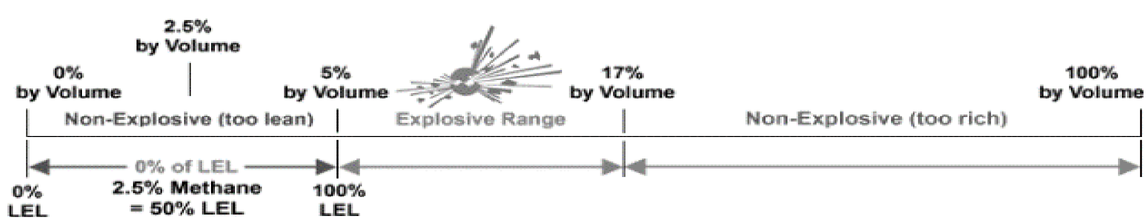


Figure 6 - Illustration of Methane LEL (5%) and UEL (17%)

2.4.4 Conclusion

Hazardous areas are arguably the most important consideration of any industrial plant due to the relatively high risk of loss of life and to a lesser extent, infrastructure damage. Knowledge is power and the more knowledge obtained through research the more development can be done towards safe and efficient operation in these otherwise dangerous environments.

Chapter 3

Field Device Power Considerations

The most appropriate method for powering a sensor in the field will depend on factors such as the power requirements of the sensor, the operating environment, and the availability of infrastructure. Field devices, such as sensors/transmitters, can be powered by a programmable logic controller's (PLC) input/output (I/O) card using voltage or current signals.

Using a PLC’s, I/O card to power field devices can be a convenient and reliable method, as it allows the field devices to be powered from a central location and can simplify wiring and maintenance. However, it may not be suitable for all applications and may require additional infrastructure, such as PLC cabinets, power supplies or remote I/O (RIO) installations.

3.1 Hard-wired

In addition to the I/O signals, power can be provided by the PLC as a stable and reliable source of power for a field device. Figure 7 provides the configuration of an analog output card in which the field equipment is powered by the signal loop and Figure 8 illustrates a field device with an external source of power.

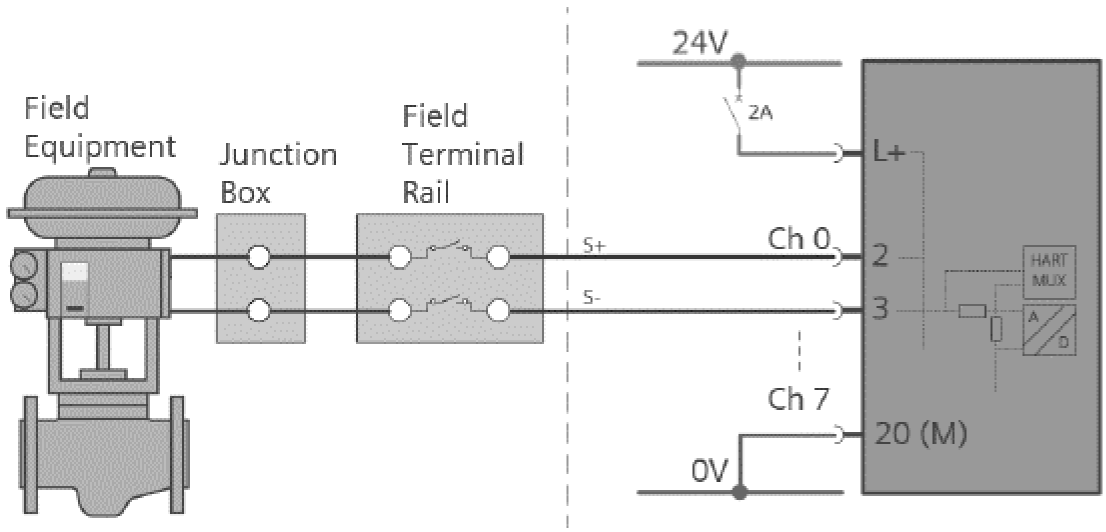


Figure 7 - Field Device Powered by AO Card

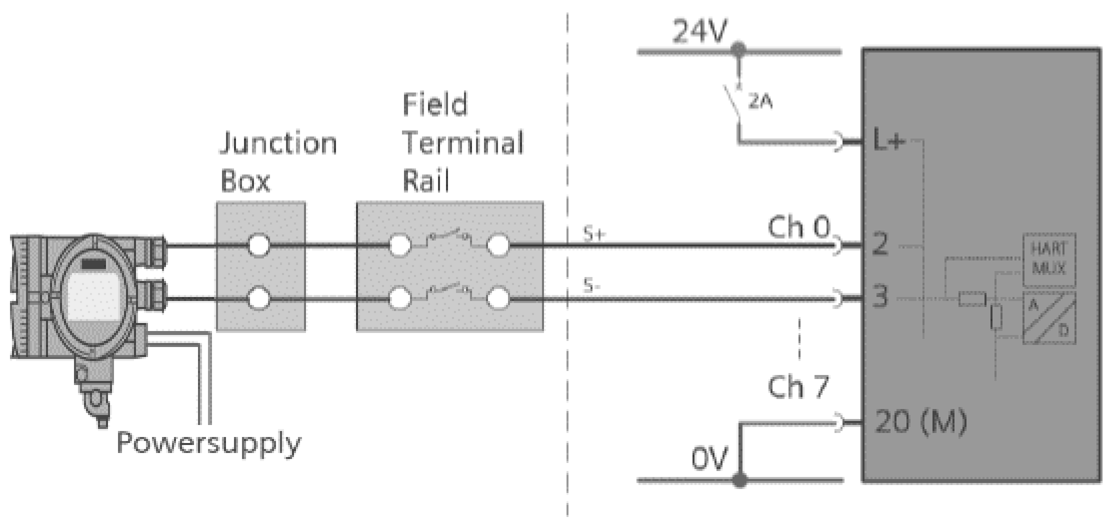


Figure 8 - Field Device Powered Externally

3.2 Portable Electronics

Many portable electronic devices are used in industrial settings and batteries are the most common method of power. These devices must generally be specifically designated for their area of application and receive special certification to avoid the potentially dangerous consequences of electronics with gas or dust.

3.3 Energy Harvesting

Energy harvesting devices are referred to as "self-sustaining" as they combine a method of energy production such as a solar cell or a piezo-electric generation method. These are integrated into the battery with a power management integrated circuit to govern the generation verses consumption of the device for power efficiency [24].

3.4 Conclusion

Providing power to all devices is a critical consideration because nothing will operate without it. There are always safety considerations for the infrastructure and personnel in the field and the Oil & Gas industry is perpetually searching for the safest, most efficient, and cost-effective solutions to operate a plant.

Chapter 4

Specifications and Design

This chapter provides a clear description of the requirements and parameters that this thesis aims to achieve and will be the criteria by which success is measured. The subsections comprehensively detail the overall fixed requirements, operating performance, design considerations, and other relevant information to the design process.

The overall design is a combination of fixed requirements and design choices which have been combined to achieve the goal of this thesis as initially stated in Section 1.1 and re-stated here for the reader's convenience:

The focus of this thesis will be exploring the potential to achieve IEC certification without the use of an enclosure leveraging the newest Bluetooth technology with the manufacturing approach that has two processing cores: one for the application code and one for network communications.

4.1 Functional & Technical Considerations

The technical considerations are contingent upon IEC compliance which is explicitly defined as presented in Section 2.4. Hazardous zone compliance for wireless transmission is theoretically determined in Section 4.1.1, Section 4.1.2 provides an overview of the main components required for this system to operate, and Section 4.1.3 follows with an operating state flow diagram.

4.1.1 IEC RF Group II Compliance

With reference to the IEC regulations specified in Section 2.4, a pulse duration that exceeds the thermal initiation time shall not exceed the power threshold in Table 2. Therefore, if the pulse is longer than 20 µs, then system power cannot be greater than 2W. If pulses are short compared to the thermal initiation time, then it must be less than the threshold energy of 50 µJ. “Short” is defined as pulses that are active for less than half the thermal initiation time and the time between two pulses is greater than three times the thermal initiation time.

4.1.2 Components

The beacon is comprised of two main hardware components:

1. BLE SoC

   A Bluetooth Low Energy System on a Chip with a high degree of power efficiency and low power profile that supports the newest and most efficient Bluetooth version. The manufacturing specifically in question is the dual-core approach, in which the network and application cores are distinct. This is to be programmed using the C-programming language in the Visual Studio Code IDE supported by the latest Nordic Semiconductor libraries for BLE development.

2. Sensor

   A low-power gas sensor for liquid petroleum gases. This is to integrate with the BLE SoC such that the beacon monitors the sensor while in deep-sleep and broadcasting is activated to notify the presence of gas to any listening devices in the vicinity.

4.1.3 Concept Design: State Flow

The fundamental system operation is presented in Figure 9 as this minimum must be possible before any other areas are progressed. “Low Power Startup” begins the state flow and immediately begins reading the analog input channel and evaluates the sensor reading to assess if a state transition is required. The network core is inactive during this stage and only activates if the sensor reading is greater than the given threshold. Once active, continuously monitoring the analog input channel until the sensor drops below the threshold which will deactivate the network core and consequently the advertisement of the alarm.

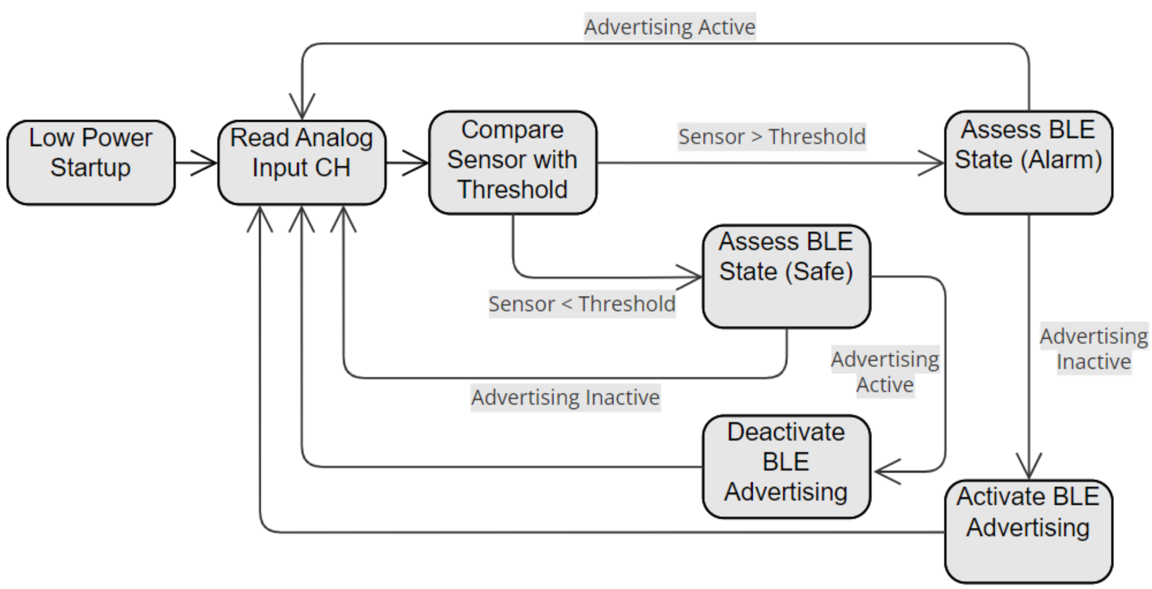


Figure 9 - SoC State-flow Diagram

4.2 Functional & Technical Specifications

A functional specification is an overview of the project's end-goal that outlines the important functionality of a device without getting into the details of how exactly it is to be accomplished. As the name implies, it deals with functionality rather than technicality and when implementing a functional specification, the method is largely irrelevant unless governed by a technical specification (or a financial specification: a "budget").

Technical specifications are design-specific and as such, they are guide for functional specifications. These specifications combine to create the success criteria of this thesis. The functional specification is driven by the concept and the design specification is manifested through the background research presented in Chapter 2.

4.2.1 Functional Specification

- BLE SoC beacon advertising the presence of liquified petroleum gas.
- Analog input channel monitoring with low power consumption.
- Pausing of advertising when gas is no longer detected.
- Battery operated.
- Operational in any of the hazardous area zones (with adherence to IEC intrinsically safe specifications).

4.2.2 Technical Specification

- Operational power in accordance with Table 2.
- RF Range: At least 3 meters.
- Open Circuit Voltage in accordance with IEC.
- Short Circuit Current in accordance with IEC.
- Transmit-Only operation “beacon” (non-connectable, non-directional)
- Eddystone-UID Standard format

4.3 Design: BLE SoC Maximizing Efficiency

Leveraging the advertising introduced in Section 2.2.5, BLE configured in broadcast mode is transmit only and will not accept pairing. Designing the beacon without point-to-point or mesh communication features, a basic broadcasting functionality can be configured and listening device could be located outside the hazardous area or be protected with a Hazardous EX enclosure.

To achieve the main success criteria of this thesis (beacon operation in a hazardous area), the new nRF5340 from Nordic Semiconductor was chosen for its design specifically for low-power applications, some key parameters as advertised are presented in Table 4.

Table 4 - Key Parameters of nRF5340

Parameters	**nRF5340**
Tx power (dBm)	-20 to +3
Tx current (mA)	2.2 (at 0 dBm)
Deep-sleep mode current (µA)	1.0
Supply Voltage (V)	1.7 to 5.5 (Optimized for 3V)

The transmission power, operating current, and deep-sleep mode current of this SoC are among the lowest currently available. Transmission power (P) listed in the data sheet can be converted between dBm and Watts using the following conversions:

$$P(dBm) = 10 * \log_{10}(P(mW)) \text{ and } P(mW) = 10^{\left(\frac{P(dBm)}{10}\right)} \quad (4.1)$$

This results in a range of transmission power between 0.1mW at -20 dBm and 2 mW at 3 dBm. Observing the maximum threshold power of 2W for IEC compliance, transmission at 3 dBm is acceptable.

4.3.1 Board Configurations and Power Simulations

The system needs to be optimized for the highest energy efficiency as possible. The basic application that operates as a BLE beacon has been downloaded to the nRF5340 and uploaded into the Nordic Semiconductor Online Power Profiler [25] for simulating power related statistics and some of the most energy-intensive operations are optimized in the following subsections of 4.3 and utilize this tool as a metric for improvement. For the design phase, this tool which is based on measured values from a model estimates the expected system values and claims to the effect of an estimated average current is within 5% of the actual value [25].

The settings that will be used across the various the simulated configurations are shown in Figure 10. Regulator efficiency in DC/DC mode varies depending on the supply voltage and the current drawn from the regulators and the advantage of using the Network Core and Application Core regulators in DC/DC mode is that the overall power consumption is reduced due to the higher efficiency this configuration presents. Low Frequency clock set to “Internal RC” as this option is the lowest power available among the options and the radio transmission power at 3 dBm for maximum range.

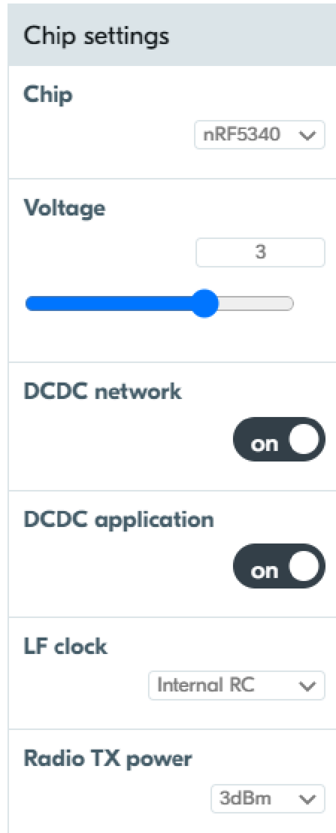


Figure 10 - nRF5340 Common Configuration

Figure 11 shows the BLE settings which contain the device “Role”, advertising interval, and transmission payload. These parameters can vary to provide benchmark information however, for the “beacon” operation, an “Advertising (TX only)” role will remain static.

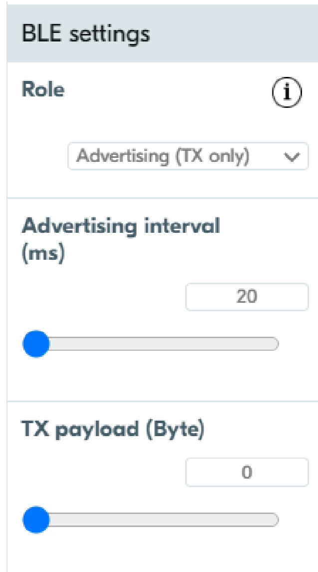


Figure 11 - BLE Settings (20ms interval, 0-byte payload)

Test setup	
Voltage	3.0 V
Regulator	DCDC
Application RAM	512 kB
Network RAM	64 kB
BLE event details	
Interval	25.00 ms
Length	2.60 ms
Data transmission	
On air data rate	1 Mbps

Current consumption	
BLE event total charge	4.60 µC
LF clock calibration current	1.6 µA
Idle current	3.7 µA
Total average current	189 µA

Figure 12 - Power Profile (20ms interval, 0-byte payload)

As shown in Figure 12, the total charge is 4.60 µC and the average current consumption of the ~30ms BLE event is 189 µA. This is as low a consumption as possible for an activation and advertising event of these configurations as it doesn't contain any transmission data. Each stage is shown in the current consumption vs time in Figure 13.

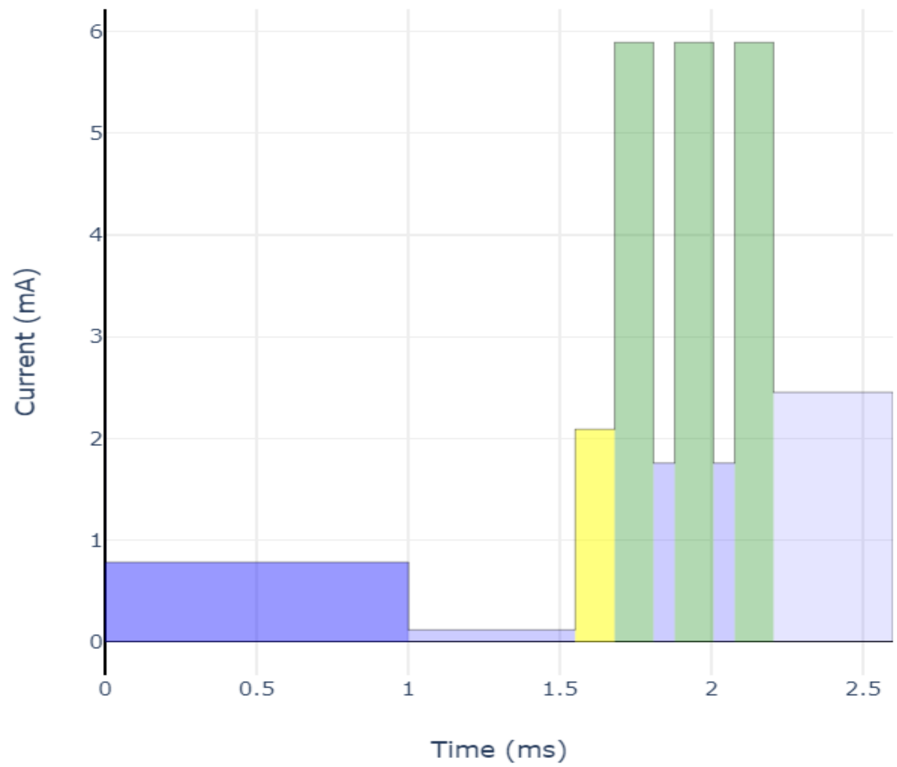


Figure 13 - Current Consumption (25ms interval, 0-byte payload)

Figure 14 - Legend: Consumption Graph

With a baseline established in Figure 12, a 20-byte payload can be introduced that would allow for an Eddystone advertising configuration Figure 15. Maintaining the advertising interval yields the following power consumption data and graph in Figure 16 and Figure 17.

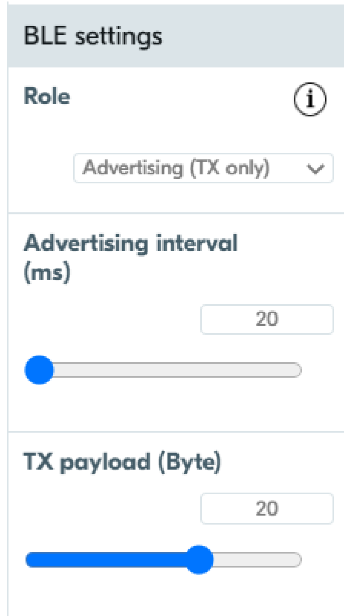
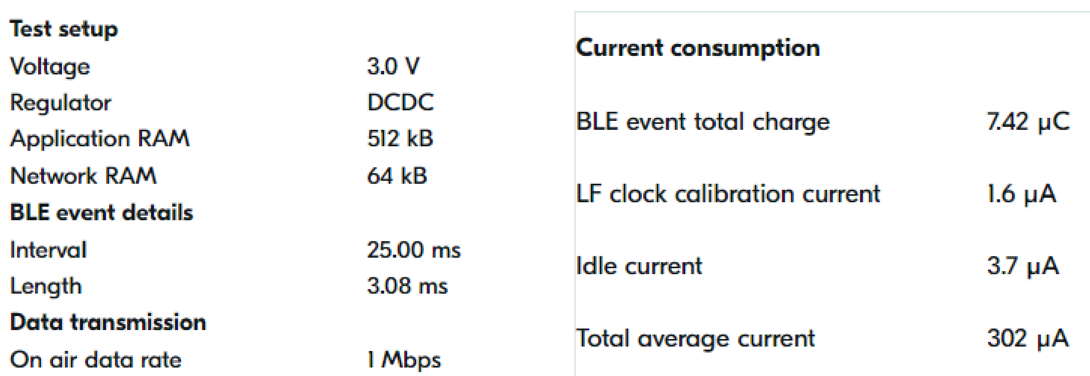


Figure 15 - BLE Settings (20ms interval, 20-byte payload)



Test setup	
Voltage	3.0 V
Regulator	DCDC
Application RAM	512 kB
Network RAM	64 kB
BLE event details	
Interval	25.00 ms
Length	3.08 ms
Data transmission	
On air data rate	1 Mbps

Current consumption	
BLE event total charge	7.42 µC
LF clock calibration current	1.6 µA
Idle current	3.7 µA
Total average current	302 µA

Figure 16 - Power Profile (20ms interval, 20-byte payload)

The total charge increases ~62% to 7.42 µC and the average current consumption is increased by ~62% as well to 302 µA. The increased duration of the advertising stages to accommodate the 20-bytes is visible in the current consumption vs time in Figure 17.

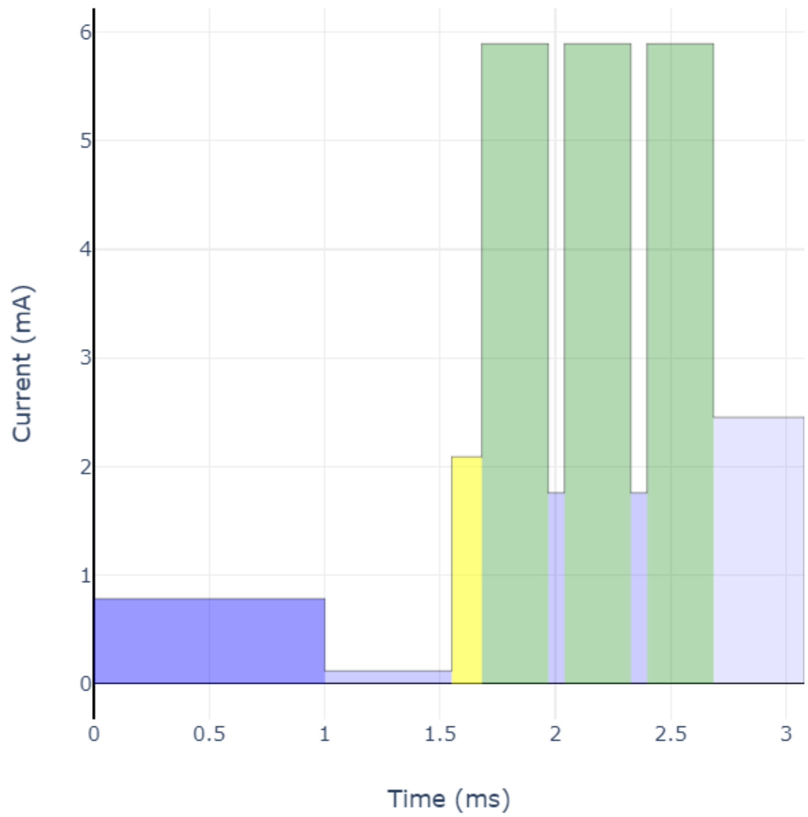


Figure 17 - Current Consumption (25ms interval, 20-byte payload)

Figure 18 - Legend: Consumption Graph

This configuration has the potential to provide meaningful information while adhering to IEC guidelines. Operating at 3V and a Total Event Charge of 7.42 µC, it is quick to convert to joules due to the following relationship between the three:

$$1\,Joule = 1\,Volt * 1\,Coulumb \tag{4.2}$$

Solving for Joules yields 22.26 μJ which is below the threshold for pulsed signals according to Table 1 however, due to the pulse durations, these transmissions would not comply with the "pulse transmission" classification due to the ratio of pulse duration and thermal initiation time as defined in the IEC 3.32.3 in Section 2.4.2.

Increasing the advertising interval to the maximum of 10240 ms will not change the BLE total charge, however it will reduce average current consumption considerably.

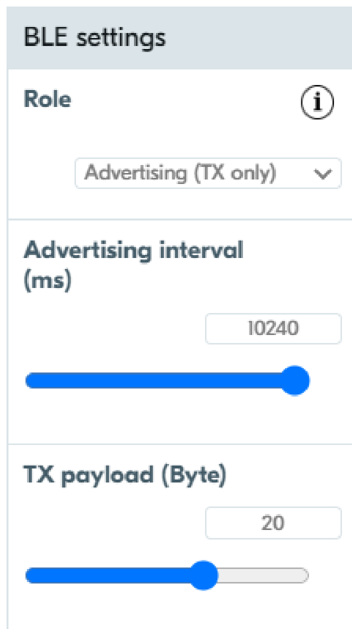


Figure 19 - BLE Settings (10240ms interval, 20-byte payload)

Yielding an average current consumption of 6.0 μA, operating at 3 V with a typical CR2032 battery with capacity up to 240 mAh, this configuration could theoretically operate in a state of broadcasting alarm with an advertising event every ~10 seconds for approximately 300 days but remain idle for over a year.

Test setup	
Voltage	3.0 V
Regulator	DCDC
Application RAM	512 kB
Network RAM	64 kB
BLE event details	
Interval	10245.00 ms
Length	3.08 ms
Data transmission	
On air data rate	1 Mbps

Current consumption	
BLE event total charge	7.42 µC
LF clock calibration current	1.6 µA
Idle current	3.7 µA
Total average current	6.0 µA

Figure 20 - Power Profile (10240ms interval, 20-byte payload)

There is a pragmatic concern with a 10 second advertising interval: if the beacon has a range of 10 meters, then personnel walking radially at 1.5 meters per second could cover the transmission distance in just under 7 seconds, potentially missing the advertisement. A more frequent advertisement would address this issue albeit at the cost of slightly higher average power consumption verified by Figure 21 to be an additional ~10%.

Test setup	
Voltage	3.0 V
Regulator	DCDC
Application RAM	512 kB
Network RAM	64 kB
BLE event details	
Interval	5125.00 ms
Length	3.08 ms
Data transmission	
On air data rate	1 Mbps

Current consumption	
BLE event total charge	7.42 µC
LF clock calibration current	1.6 µA
Idle current	3.7 µA
Total average current	6.7 µA

Figure 21 - Power Profile (5120ms interval, 20-byte payload)

4.3.2 CPU Clock Frequency

The system clock frequency dictates the speed a particular routine is processed and as a result the energy consumption required during execution time. A faster clock speed means faster processing at the price of higher current expenditure. Each device has a certain minimum and maximum clock frequency requirement, which must not be violated. The nRF5340 has an application core which runs the routines with a variable clock speed between a minimum of 64 MHz and 128 MHz. The system clock frequency may need to be adjusted to reduce the current consumption to accommodate the IEC specifications however is set to 64 MHz for this design.

4.3.3 Optimize Shared Memory-Based Communication

A common method which allows the different cores in asymmetric multiprocessor systems to cooperate is the use of a shared memory-based communication. The nRF5340 is a dual core device and has this implementation. Disabling the “serial logging” in the application processor and HCI_RPMSG transport should improve efficiency.

4.3.4 Low-Power Device Bootup

When an embedded device is powered on, it must complete a bootup procedure before it can execute application code. A standard bootup sequence is as follows:

a. Initializing memory

b. Setting interrupt vectors

c. Configuring peripheral and common registers

d. Initializing external clocks (if any)

These operations require CPU processing time, which in turns consumes energy (modified by processor clock speed). The energy consumption has several contributing factors such as the type of device used, system clock frequency, memory/register set size, and setting up any external clocks. The bootup process is relatively power-intensive and is an important factor in optimization to prevent excessive energy consumption demands.

4.3.5 Low-Power System Startup

Once application code begins to execute, individual peripherals in the system are typically started. Peripherals could be internal to the device, such as an Analog-Digital-Converter (ADC), or may be external to the device, such as a gas sensor. To enable system and device power management the following must be added:

CONFIG_PM: Enables the board to implement extra power management policies whenever the kernel becomes idle. The kernel informs the power management subsystem of the number of ticks until the next kernel timer is due to expire.

CONFIG_PM_DEVICE: Enables the device power management interface. The interface consists of hook functions implemented by device drivers that get called by the power manager application when the system is going to suspend state or resuming from suspend state. This allows device drivers to do any necessary power management operations like turning off device clocks and peripherals. The device drivers may also save and restore states in these hook functions.

4.3.6 Staged Application Processing

Devices run application routines which require their own CPU bandwidth. Such routines include configuring peripherals, reading sensor data, evaluating calculations, and managing events and interrupts. Placing the system into a low-power mode between each stage with a method of waking up such as a watchdog timer is an effective way at increasing efficiency. The system will remain in idle/low-power mode for most of its operation, and as such the current requirements during these modes must be as low as possible.

4.4 Beacon Advertising: Eddystone

After the system is optimized for power consumption, the details of the operation must be determined adhering to the principles and concepts established for power optimization best practices. The beacon formatting is to be designed using the Eddystone specification. This specification is already recognized by many devices by default and removes the requirement to design a Universally Unique Identifier (UUID) as well as the implementation on every device that may attempt to listen.

4.4.1 Specification

Eddystone has the following 4 frame types, however UID is chosen for this design:

Eddystone-UID: Broadcasts a unique identity (Unique ID) code that allows apps to interpret and act on the information.

Eddystone-EID: Broadcasts an encrypted rotating identifier to increase the security of the protocol, but otherwise acts similarly to the UID frame.

Eddystone-TLM: Broadcasts information about the beacon. This can include battery level, sensor data, or other relevant information to beacon administrators. It must be accompanied by another frame type to be usable as a beacon.

Eddystone-URL: Broadcasts a URL of at most 18 characters that redirects to a website that is secured using SSL.

4.4.2 Eddystone-UID: Frame Specification

The UID frame is encoded in the advertisement as a Service Data block and is recognized as the Eddystone service UUID. With 20 bytes, Table 5 presents the Eddystone-UID frame capable of broadcasting a unique 16-byte Beacon ID composed of a 10-byte namespace and a 6-byte instance:

Table 5 - Eddystone-UID Frame

Byte Offset	**Field**	**Description**
0	Frame Type	Value = 0x00
1	Ranging Data	Calibrated Tx power at 0 m
2	NID[0] – NID[9]	10-byte Namespace
12	BID[0] – BID[5]	6-byte Instance
18	RFU	Reserved for Future Use
19	RFU	Reserved for Future Use

The ranging data can be used by the listening device to determine approximately how far away the beacon is and thus how far away an individual may be from the harmful gas. The Beacon ID can be used to map a device to a record in external storage of a listening device. The namespace may be used to identify an area or zone of beacons, and the instance bytes for individual devices in the group. This would, in practice, be pre-programmed into each beacon with a field tag number for easy recording and identification. A fictional tag has been assigned in the name space of this design for proof-of-concept.

4.5 Design: Gas Sensor

This subsystem measures the parameter of interest, in this design a gas sensor provides an input signal to the BLE SoC to monitor and compare against a threshold to act as a trigger for beacon activation. Considerations include low power consumption, sensitivity to the target gas, a long life and ease of integration into the beacon.

4.5.1 Selection

The TGS2610-C00 was selected as the sensor for this design. It is a semiconductor type that combines high sensitivity to liquefied petroleum gas as can be seen in Figure 22 and low power consumption with high durability which results in a long operating life.

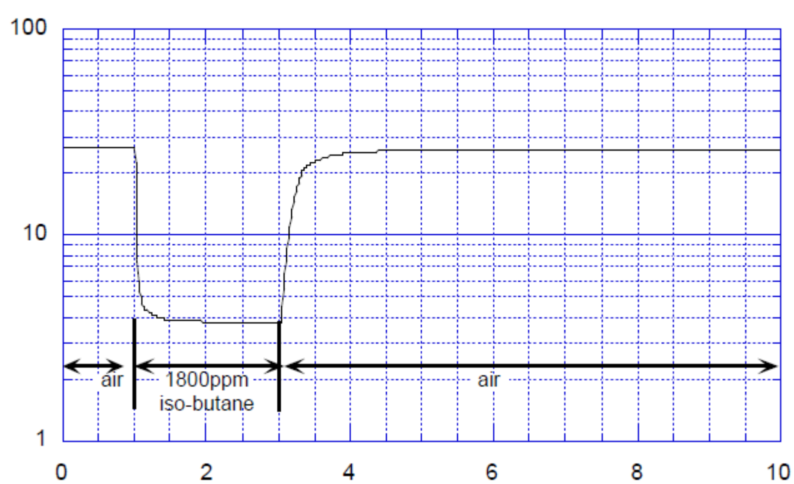


Figure 22 - Gas Response to Iso-Butane: Resistance (kΩ) vs Time (min)

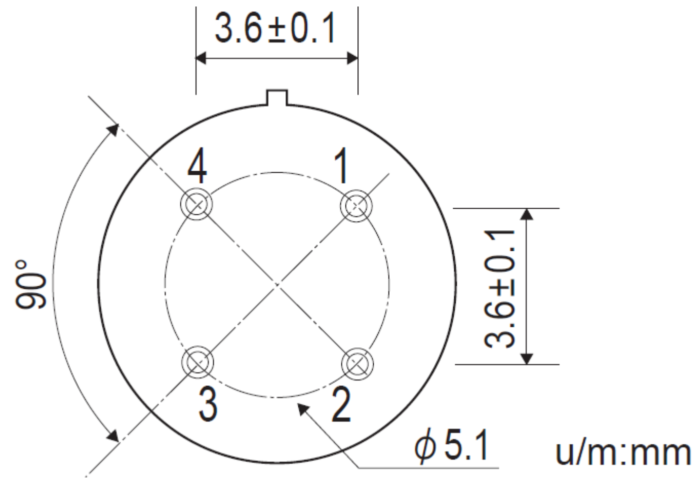


Figure 23 - TGS2610-C00 - Bottom View

Pin Connections:

1: Heater

2: Sensor electrode (-)

3: Sensor electrode (+)

4: Heater

4.5.2 Measuring Circuitry

This sensor has two voltage requirements: a heater voltage and circuit voltage. The integrated heater maintains the sensing element at an optimal temperature required for accuracy. The circuit voltage allows measurement across the load resistor which is connected in series with the sensor. The nRF5340 development board can provide power for both using the 5V output pin. The load resistance is chosen to optimize the alarm threshold value, keeping power dissipation (Ps) of the semiconductor below a limit of 15 mW: power dissipation will be highest when the value of Rs is equal to RL on exposure to gas.

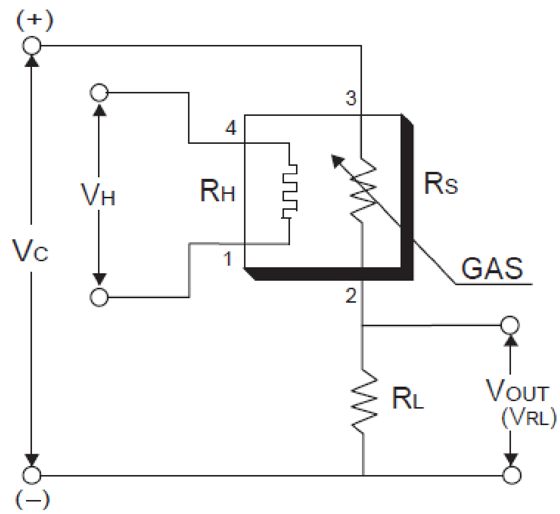


Figure 24 - TGS2610-C00 Measuring Circuit

The ever-present P_H (the power dissipation from the heater element, R_H) is to be considered throughout the entire operation of the circuit and is given by:

$$P_H = \frac{(V_H)^2}{R_H} = \frac{25V^2}{89\Omega} = 0.280\ W = 280\ mW \qquad (4.3)$$

With the expectation that the remaining circuitry does not exceed approximately 1.7 Watts, Group IIC threshold power of 2 Watts will be respected.

With a source voltage V_C of 5 V, a limitation on the semiconductor's power (P_S) of 15 mW and range of resistances for Rs due to gas exposure between 1 kΩ and 10 kΩ, selecting 1 kΩ for the calculation, the voltage across the load resistor V_{RL} can be determined.

$$P_S = \frac{(V_C - V_{RL})^2}{R_s} \qquad (4.4)$$

Solving for V_{RL} shows a minimum voltage of 1.125 V is acceptable to maintain a maximum P_S of 15 mW. Using this voltage, a simple voltage divider calculation between R_S of 1 kΩ and R_L results in a minimum R_L value of 290 Ω.

$$V_{\mathrm{RL}} = V_{\mathrm{C}} * \frac{R_{\mathrm{L}}}{(R_{\mathrm{S}}+R_{\mathrm{L}})} \tag{4.5}$$

That same calculation solving for V_{RL} using the maximum R_S of 10 kΩ and the minimum R_L of 290 Ω results in 150 mV. Considering a reasonable range for the analog input channel of the nRF5340 DK, a maximum V_{RL} of 3V is selected which yields an R_L of 1.5 kΩ and confirmed P_S of 4 mW to observe the semiconductor limitation. With reference to Figure 22, when this sensor is exposed to 1800 ppm of Iso-Butane R_S drops to about 4 kΩ dictate that the beacon alarm be set at approximately 1.36 V.

$$V_{\mathrm{RL}} = 5 * \frac{1500}{(4000+1500)} = 1.36\,V \tag{4.6}$$

This voltage equates to an Analog-Digital-Converter value of about 450 (~1318 mV) on the nRF5340 DK Analog Input channel P0.04 and will be the alarm threshold for Gas Detection and signal to begin advertising.

4.6 Conclusion

With the design finished, thresholds determined, code written and expected results determined via simulation and calculations it is now feasible to move on and prototype the design to gather real-world data through experimentation and, hopefully, validate the design.

Chapter 5

Experimental Validation

The realization of this design includes the SoC programming as per Figure 9 - SoC State-flow Diagram, power efficiency considerations applied as per Section 4.3, constructing the measuring circuitry for the gas sensor as per Figure 24 - TGS2610-C00 Measuring Circuit, preparing the nRF5340 development kit for current measurement and installation of the associated iOS application for Bluetooth scanning from Nordic Semiconductor. Measurements can be taken in advance of gas exposure by substituting a potentiometer for the TGS2610-C00 and manually manipulating the resistance values, specifically confirming the alarm threshold by reading the ADC console via Visual Studio Code IDE console.

5.1 Hardware

The hardware used for the experimental beacon construction is as follows:

- nRF5340 Development Kit
- Power Profiler Kit II
- TGS2610-C00
- B103 Potentiometer: 1 kΩ to 10 kΩ range
- Other miscellaneous electronic components (for measuring circuit)

The Power Profiler Kit II isn't required for functionality; however, it is essential for obtaining accurate power consumption data which will be critical to verify the design and ultimately the safety of this beacon in a hazardous environment.

5.1.1 nRF5340 Development Kit

The nRF5340 Development Kit allows for easy access to the SoC features. The antenna is of particular focus and concern of charge build-up.

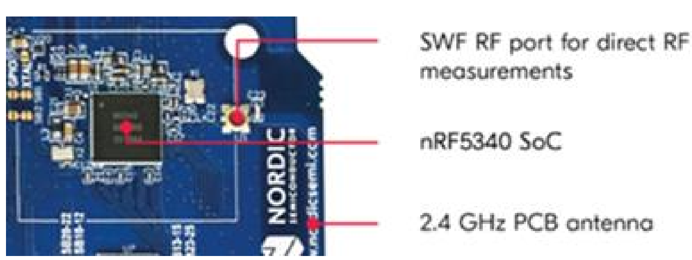


Figure 25 - nRF5340 Development Kit Focus

5.1.2 Power Profiler Kit II

The PPK2 is driven by the nRF52840 System on Chip (SoC), which uses its analog-to-digital converter (ADC) to measure a voltage drop over a series of measurement resistors. Resistor values are used to calculate the power consumption. The PPK2 has five different measurement ranges, which are managed by an automatic switch circuitry. The configuration with the nRF5340 Development Kit is shown in Figure 26 with specific preparations made to the board, primarily the removal of the SB40 trace to separate the P22 pins for current measurement.

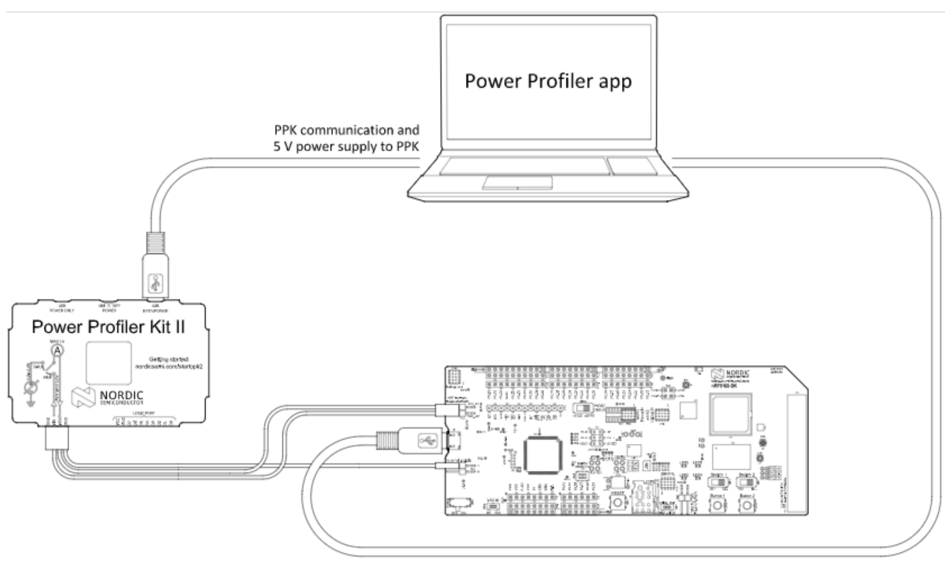


Figure 26 - Power Profiler Kit Configuration

5.2 Software Tools

The following software was used to program the SoC and for experimentation:

- Visual Studio Code (IDE) with nRFConnect for VS Code Extension Suite
- Power Profiler (application for the Power Profiler Kit II)
- nRF Connect for iOS to scan available BLE devices and diagnostic information

With this software it is possible to verify successful beacon operation (nRF Connect for iOS), monitor the terminal communication information (Visual Studio Code) and measure the power consumption (Power Profiler Kit II) of the beacon in real-time.

5.3 Lab Data Collection

With the design complete and simulations providing insight into reasonable expectations from Chapter 4, this section details the data collected by this thesis' design. As mentioned in the chapter introduction, the lab configuration used a potentiometer to mimic the TGS2610-C00 resistance range.

The testing was conducted in an open area with direct line of sight between the beacon and cell phone that was running "nRF Connect for iOS" to provide the data in Section 5.3.1. Distances were measured and marked at 50 cm intervals radially from the beacon and the readings were captured as the alarm was detected. This application uses the delta between the known transmission power and power received to estimate the distance to the source (beacon). The readings correlated approximately with the measured distances during the initial setup and resulted in their corresponding signal attenuations.

5.3.1 Data: nRF Connect for iOS

Data from this iOS application demonstrates a successfully accomplished functional specification, with detection possible at practical distances despite the low transmit power and relatively infrequent advertising rate of ~5120 milliseconds. Measurements were taken at increasing distances from the beacon and presented below starting with Figure 27 - Beacon Advertising (Near source).

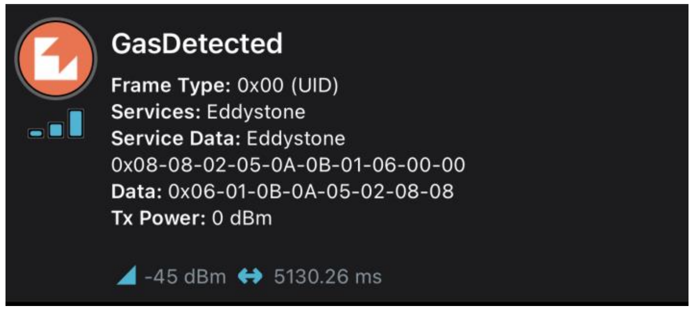


Figure 27 - Beacon Advertising (Near source)

As the scanner is essentially directly next to the transmitter, despite the dBm loss, the strength is effectively as good as can be expected.

Figure 28 - Beacon Advertising (~1.5m)

Figure 28 maintains a strong signal at approximately 1.5 meters away from the beacon.

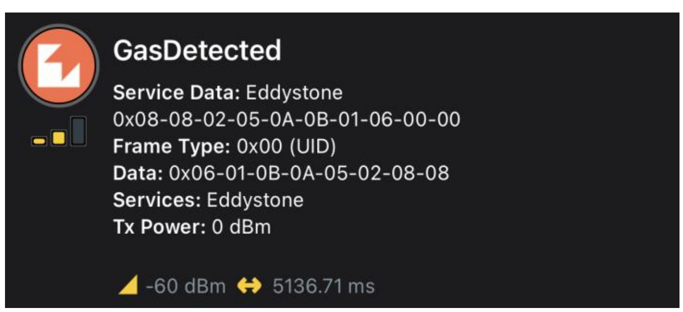


Figure 29 - Beacon Advertising (~3m)

At around 3 meters, the signal strength began to indicate medium strength. There is an attenuation difference of 10 dBm between 3 meters and the previous 1.5 meters. In ideal conditions, the inverse square law dictates a signal attenuation of 1/4 with a doubling of distance from the source yet a 10 dBm delta was measured. This could be accounted for by other signal interference and non-ideal devices. Figure 30 shows the decrease in signal strength of each advertising event detected by the scanner.

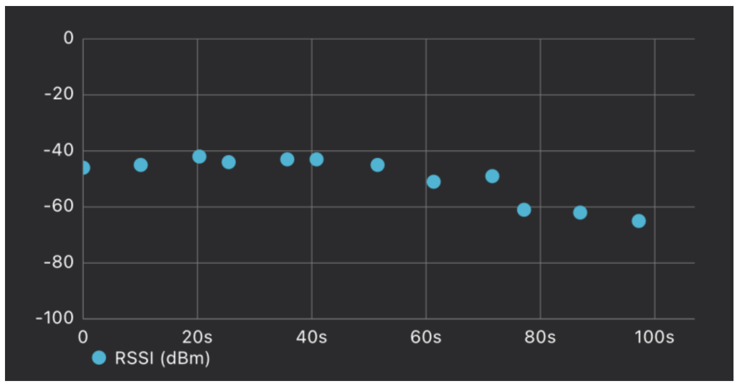


Figure 30 - RSSI (dBm) while moving away.

The maximum range in laboratory conditions, (despite potential external RF interference), achieved a range of approximately 6 meters before becoming unreliable.

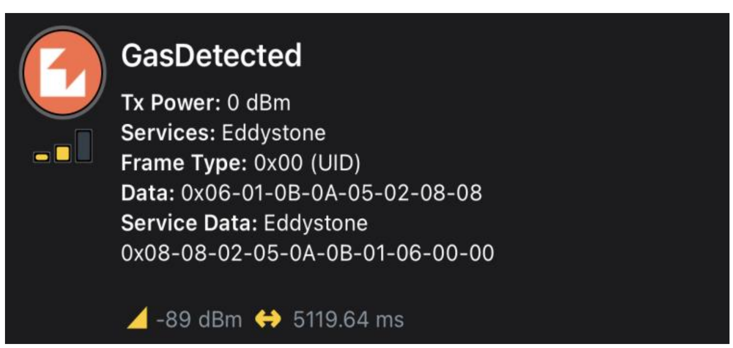


Figure 31 - Maximum range (~6m)

5.3.2 Data: Visual Studio Code

Using the COM3 port to interface with this software, the ADC raw value, converted value to millivolts and the threshold state transitions following the state-flow diagram's implementation are visible during operation.

ADC-Value: 448

ADC-Voltage: 1312 mV

No Gas Detected.

ADC-Value: 503

ADC-Voltage: 1473 mV

Gas Detected, beacon activated.

ADC-Value: 512

ADC-Voltage: 1500 mV

Gas Detected.

ADC-Value: 271

ADC-Voltage: 793 mV

Gas No Longer Detected, beacon deactivated.

ADC-Value: 237

ADC-Voltage: 694 mV

No Gas Detected.

5.3.3 Data: Power Profiler Kit II

The power profiler allows for accurate current measurements drawn by the development kit and sensor circuitry. It provides the ability to analyze power data and charge accumulation. The following screenshots present relevant current data. This captures only the current consumption required for the board to operate and run through the sensing circuit not the perpetual power dissipation of the heater element (280 mW) and as such, that power has been added to the maximum current consumption's power equivalent to confirm a respected threshold.

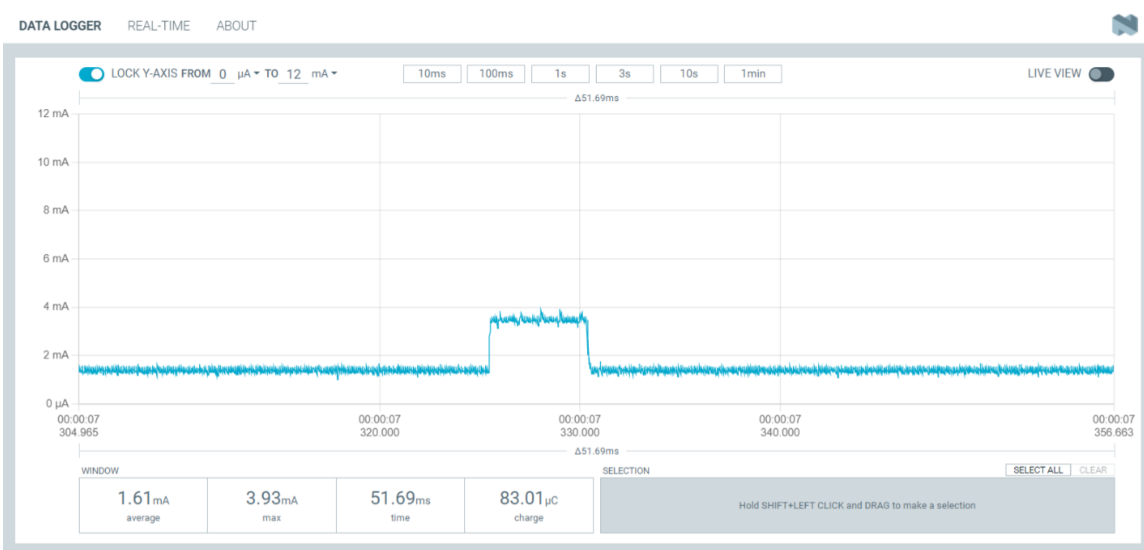


Figure 32 - Current drawn during code execution

The SoC has a 5 second sleep between every code execution and therefore completed state-flow cycle. This value was chosen based on the advertising interval. Each execution averages about 3.45 mA, with a charge of 17.27 µC over 5 milliseconds. Adding 280 mW to the maximum current observed results in 292 mW.

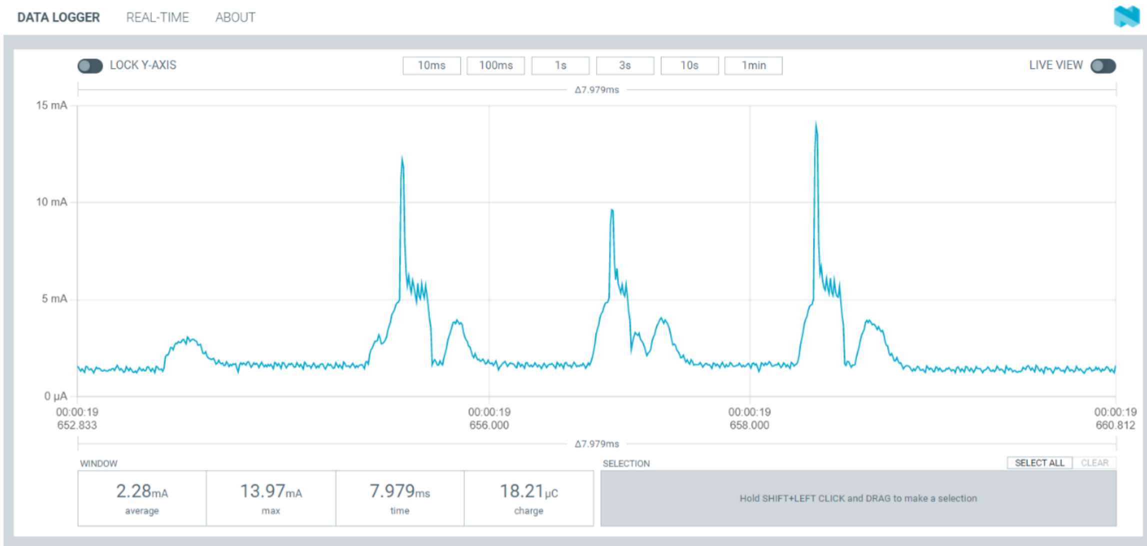


Figure 33 - Current drawn during Advertising event

The current consumption shown in Figure 33 maps to the consumption graphs of the online power profiler used in Chapter 4 for preliminary design. The initial current draw is the "Pre-processing" phase. Then there's a brief spike for starting the radio and immediately the first advertising channel event occurs, followed by a short stand-by. The advertising on each of the 3 advertising channels occurs and is followed by the post-processing phase and then sleep before looping main(). Adding 280 mW to the maximum occurrence of 13.97 mA at 3V (42 mW) results in 322 mW.

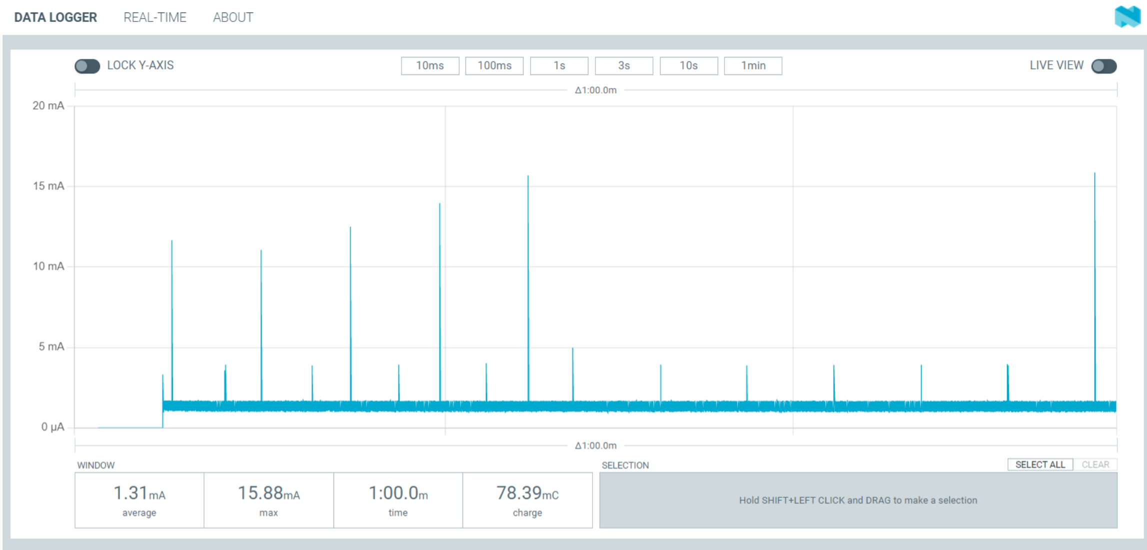


Figure 34 - Normal Operation and Gas Detected Advertising Events

Figure 34 illustrates a test scenario in which the "gas detected" is staggered for code execution visibility and demonstrates detection (voltage above threshold), no detection (voltage dropped below threshold) and detection again. The average of 5 seconds power consumption during sleep and including one instance of code execution consumption averages 1.39 mA with a charge of 6.96 mC. Similarly, a 5.125 second span which includes both an advertising event and a code execution averages 1.40 mA and a charge of 7.15 mC. Adding 280 mW to the maximum occurrence of 15.88 mA at 3V (47.6 mW) results in 328 mW.

Figure 35 shows both the code execution and advertising current consumption in the same profiler frame for illustration.

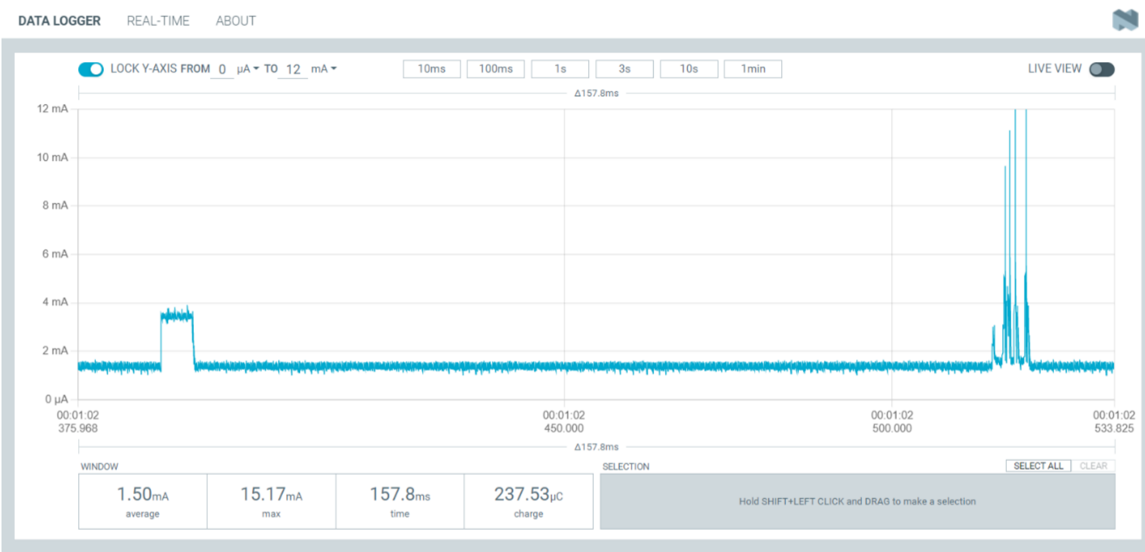


Figure 35 - Code power and Advertising power in the same frame

5.4 Exposure to Gas

With the laboratory environment data collected, functionality confirmed, and thresholds verified, the potentiometer was replaced in the circuit by the TGS2610-C00 sensor. When exposed to butane, the sensor behaved as advertised responding with the resistance profile stated in the datasheet. Using a container to house the beacon prototype and a small bottle of light butane to fill it, the beacon inside functioned as expected based on the laboratory results and the thesis' design was proven by functioning correctly and safely in this hazardous environment.

Chapter 6

Assessment of Findings

Results from the realized design are presented and compared with the simulation results and discrepancies are discussed where potential sources are identified. Testing considerations are then reflected upon.

6.1 Simulation vs Field Results

The simulation data from the Online Power Profiler in Section 6 provided valuable insight into the expected results when deployed and executed on the nRF5340. The advertising events were reasonably accurate (within the stated 5% margin of error) as was the power consumption of the various phases such as start-up, advertising, pre- and post- processing. With the addition of the heating element, all results still produced current consumption below a desired 2 W threshold.

6.2 Discrepancies

Using the Power Profiler Kit with the actual development board, a higher average current was observed than predicted by the simulation. However, the simulation was only accounting for the code and could not calculate processing required for the analog input channel nor the power drawn from the sensing circuitry for the TGS2610-C00. Additionally, the profiler power code was examined during advertising events and did not include idle time that in practice could be minutes to days to months and ideally never; the calculations were performed with the assumption of an advertising event every cycle.

6.3 Testing Considerations

Although the beacon operated successfully as designed, there are some considerations that could prove the testing more accurately. As mentioned, this aspect of the testing is rather informal, as a proper certifying body is required to make such a claim as "appropriate" for hazardous areas and the following two factors are considerable: Development Kit and butane ppm.

The deployed beacon is prototyped on the nRF5340 development kit, which, for better or worse is simply different than a finished product without the superfluous circuitry and additional features possible with the board.

The environment in which the beacon was tested was not controlled for the concentration of butane. Filling the container was able to trigger the sensing circuit, however it remains unverified if this concentration was indeed between the Lower Explosive Limit (1.8%) and Upper Explosive Limit (8.4%) of butane percent by volume required for ignition.

6.4 Conclusion

An analysis of the findings provides valuable insight towards the goal of certification with an official authority. The discrepancies between simulation and reality as well as the testing considerations will help refine the overall design moving with future work.

Chapter 7

Conclusion

With the functionality achieved as set out by the functional and technical specifications determined Section 4.2, this thesis' work is considered a success. A foundation has been developed for a Liquid Petroleum Gas detection beacon that functions in a hazardous environment and may be integrated into existing wearable portable gas detectors with the requirement of adding Bluetooth scanning and does not require transmission. Depending on desired functionality and hazardous area application, more detailed information may be implemented. This thesis followed a methodical and structured approach to design which ultimately resulted in accomplishing desired results.

7.1 Lessons Learned

The goal to leverage the newest Bluetooth Low Energy and Software on a Chip technology has provided valuable insight into the fundamentals and foundational operation of Bluetooth, which is an everyday technology used by everyday people, not limited to certain industries or professions.

With ten years of engineering experience in industrial controls and safety system design, it was interesting to delve into the depths of more uncommon industry standards and their presentation as a part of this thesis' research and literature review. The novel combination and application to operate within established standards has value for this sort of pre-warning system for environmental/hazardous area awareness for the safety of personnel.

Creative approaches to operating within limitations come with pragmatic trade-offs. For example, during the design phase it was considered to disable two of the three advertising channels, effectively reducing the transmission output power by 66%. However, in practice this resulted in a listening device missing the beacon's advertisement and given the nature of this application, missing this notification is unacceptable. Another pragmatic adjustment was the advertising interval was increased to accommodate the average walking speed of North American males aged 20-50 years old.

7.2 Future Work

This thesis has proven to be a foundation for further exploration in this direction and potentially safe implementation of this type of technology in otherwise dangerous environments. With an expansion on Section 3.3 to implement an energy harvesting system, battery life would no longer be a consideration and the power profile data obtained from this design can be directly used for appropriate selection and implementation with a Power Management Integrated Circuit for current management to align with general code execution and detection advertisement.

Integration into a portable Bluetooth scanner that can expand features such as area identification based on the Eddystone UID information for specific tag type, gas type, area of exposure and potentially other information such as length of alarm. A central device could be as simple as a red light and sound to signal detection or more complicated designs that include an interface for viewing data, tag information and other such functionality that may be deemed useful or necessary.

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